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ORIGINAL ARTICLE

Ultrasonic assisted grinding of advanced materials for biomedical and aerospace applications—a review

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Abstract This paper presents a review on ultrasonic-assisted grinding (UAG) of advanced materials, specifically investigating the effects of ultrasonication on material removal rates (MRR), grinding forces and energy, tool wears, wheel loading, residual stress and surface/subsurface damages. It compares the performance of UAG of ceramics and super alloys for biomedical and aerospace applications, with the performance of the conventional grinding (CG) techniques. The effects of the UAG process parameters on the MRR, grinding ratio, tool life, residual stresses and surface/subsurface damages were also investigated. Studies on the performance of the UAG process in the machining of brittle and ductile materials have shown that the introduction of the ultrasonic system to the grinding process helps to increase the material removal rates significantly, and consequently reduces the surface roughness, grinding forces and subsurface damages. The self-sharpening phenomenon found in the UAG process was realised to be responsible for the improved machining performance of the UAG process. Furthermore, the application of biodegradable lubricants (vegetable oil based) to the grinding process was also found to improve the machining performances of the UAG process, achieving almost the same performance as the non-biodegradable lubricants. As such, the use of the biodegradable lubricants in the grinding process was encouraged due to its economic benefits, and environmental friendliness.

Keywords Ultrasonic assisted grinding (UAG) · Ceramic · Super-alloys · Biomedical and aerospace applications

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1 Introduction

Advanced engineering ceramics and super alloys such as alumina, silicon nitride, zirconia, and Inconel have seen rapid rise in their applications across a wide range of industries, such as automotive, aerospace, nuclear industry, refractory insulators, electrical/electronics, and defence industries because of their excellent physical, mechanical, and chemical properties [1–5]. They are characterised by the following: high melting point, low density, good resistance to thermal shocks, resistance to oxidation reactions, very high hardness, high strength at elevated temperatures, chemical stability, low thermal and electrical conductivities, low friction and high wear resistance [1, 2, 6].

Cutting is the most popular and feasible process for manufacturing ceramics and super alloys. Some methods used to fabricate or cut the super hard materials include forming, grinding, shearing, etc. Interests in machining of the advanced ceramic materials have substantially grown due to their widespread usage in precision components [1, 7].

An important requirement during the manufacture of ceramic parts is the reliability of the machining process. In spite the significant advancements made in near-net shape technologies, the abrasion grinding method using diamond or cubic

boron nitride (CBN) wheels is still the predominant method of machining the ceramic components [8]. Conventional grinding (CG) utilizes the gliding action of a super-hard tool over the workpiece at very high speeds. This process has been utilized in advanced machining to obtain improved surface integrity and high dimensional accuracy/tolerance in different engineering materials [9, 10]. Grinding has been estimated to account for more than 23% of machining advanced materials and ceramics in industries, whilst consisting more than 80% of the costs in the manufacturing process [11–13]. The various limitations associated with the CG process led to the mass exodus towards investigations, aimed at improving the performance of the grinding process economically, reliably, etc. [2, 14, 15].

Due to the properties of the ceramic materials such as high hardness, low fracture toughness and brittleness, the ceramic materials were classified under difficult to machine materials. Also, compared with their metallic counterparts, the ceramic materials are much harder and hence more prone to brittle fractures [16–19]. The setback mainly associated with grinding of the ceramic materials is their brittleness which results in high cutting forces, edge chipping and microfractures during the process of cutting [19–22]. The limitations associated with the cutting of ceramics materials are among the major impediments to their widespread usage [2]. Moreover, different kinds of deformations such as sub-surface damages, micro-cracks [2, 23], pulverised layer [24], plastic deformations, and tool/wheel wear are also found in the CG process. These deformations were also found to be accompanied by high grinding forces and heat generation [25].

Recently, there has been more focus on hybrid cutting processes used in the cutting of the ceramic components. They include processes like ultrasonic-assisted grinding (UAG), laser-assisted thermal grinding (LAG), ultrasonic-assisted turning, etc. The hybrid processes, as observed by previous research works, have brought about significant improvements to the efficiency and surface quality during machining of the advanced materials [26–28]. The hybrid machining process can henceforth be regarded as a favourable machining method for the ceramic materials [14].

Several investigations have been done to understand the effects of ultrasonic vibration during the grinding of hard and brittle materials. The outcome of these investigations highlights that the surface roughness, material removal rates, and strength of the ground components were improved significantly by the ultrasonication of the grinding process. Furthermore, the grinding forces and tool wears were found to be decreased considerably by the ultrasonic vibrations [20, 29–34].

Ultrasonic-assisted grinding involves simultaneously applying ultrasonic vibrations to the workpiece in two directions; it is developed such that it combines the impact of material removal phenomenon of ultrasonic-aided lapping with high-speed abrasive grinding [35, 36]. In UAG process, the ultrasonic vibrations are produced by transforming electrical signals from piezo-electric or magnetostrictive converters into linear motions [3, 37]. It has proved to be a cost-effective method of machining super hard materials [22, 27, 29, 34, 38–40]. The UAG process has been widely used in the cutting of super-hard materials such as structural ceramics, glass, super alloys, metallic composites and carbonated plastic composites [32, 41].

Although the UAG process has a lot of advantages compared to CG as elucidated, it is yet associated with many limitations such as micro-cracks, subsurface damages, residual stress and in some cases, reduced surface quality [42]. However, an in-depth investigation of the effects of the UAG process parameters on the performance of the process during grinding of advanced materials was required, so as to optimize the machining process. By so doing, the productivity and widespread usage of the advanced ceramic materials would be increased considerably for the aerospace and bio-medical applications [2, 43, 44].

This paper provides a comprehensive review of the current achievements and limitations of the UAG process with emphasis on the current limitations to provide grounds for future research works. It assesses the basic principles and performance of the ultrasonic-assisted grinding process, in comparison with the CG process regarding productivity, physical properties, part quality, etc.

1.1 Grinding wheels used in cutting superhard materials

The tool used to perform the grinding operations is referred to as the grinding wheel. Grinding wheels are important parts of the grinding process and are made up of many tiny abrasive grains held by abrasive bonding material as illustrated in the structure of grinding wheel shown in Fig. 1. The bonding material does not participate in cutting during the grinding process; rather, its primary function is to hold the grains together. Standard grinding wheel bonds includes vitrified, resinous, silicate, shellac, rubber, metallic and electroplated bonds. The abrasive grains (superhard material) and bond (fixative material) are the main components of the grinding wheel. The space between the abrasive may be partially or wholly filled with the bond material. Also, the performance of the grinding wheel was a function of abrasive material, abrasive grain size, bond material, porosity, concentration and the strength of abrasive bond. The abrasive grains are characterized by higher hardness, wear resistance, toughness, friability, etc. The main parameters of the grinding wheel are grain size, bond material type and wheel structure. The categories of abrasives mainly used as grinding wheels are either natural or synthetic. The artificial abrasives most commonly used are aluminium oxide, silicon carbide, cubic boron nitride, and diamond. Furthermore, the choice of the wheel types depends on the characteristics of the workpiece material, desired